The Top mass in Hadronic Collisions

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Pramble

This talk is about heavily debated issues on the top mass measurement in hadronic collisions.

Summarized in arXiv:1712.02796, contribution to the volume

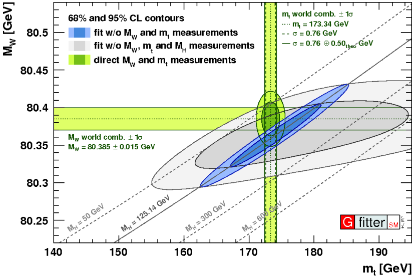
> *"From My Vast Repertoire – The Legacy of Guido Altarelli."*

It is a topic that inspires discussion, and that needs discussion.

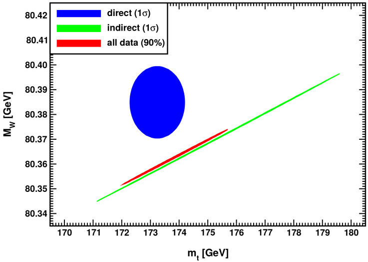
outline

- Is the top mass important?
- Current measurements and “Interpretation”
- The “Monte Carlo Mass” concept
- Perturbative issue
- Non Perturbative issue
- The mixing of the two
- Do we need the “Monte Carlo Mass’ concept?

Top and precision physics



From PDG:



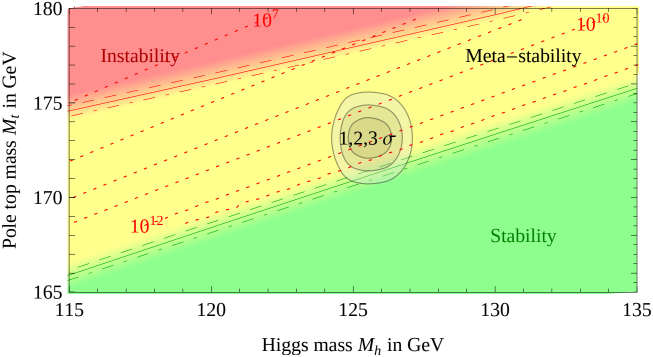
$$\Delta G_\mu / G_\mu = 5 \cdot 10^{-7}; \quad \Delta M_Z / M_Z = 2 \cdot 10^{-5};$$

$$\Delta\alpha(M_Z)/\alpha(M_Z) = \begin{cases} 1 \cdot 10^{-4} (\text{Davier et al.; PDG}) \\ 3.3 \cdot 10^{-4} (\text{Burkhardt, Pietrzyk}) \end{cases}$$

M_W can be predicted from the above with high precision, provided M_H and M_T (entering radiative corrections) are also known (and depending on how aggressive is the error on $\alpha(M_Z)$).

Top and vacuum stability

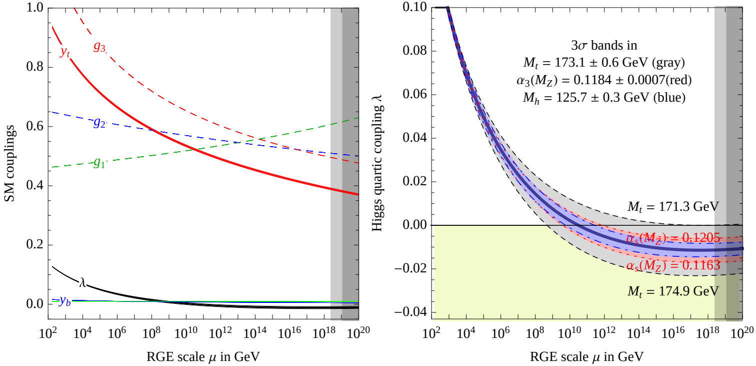
Degrassi et al. 2012



With current value of M_t and M_H the vacuum is metastable.
No indication of new physics up to the Plank scale from this.

Top and vacuum stability

Degrassi et al. 2012



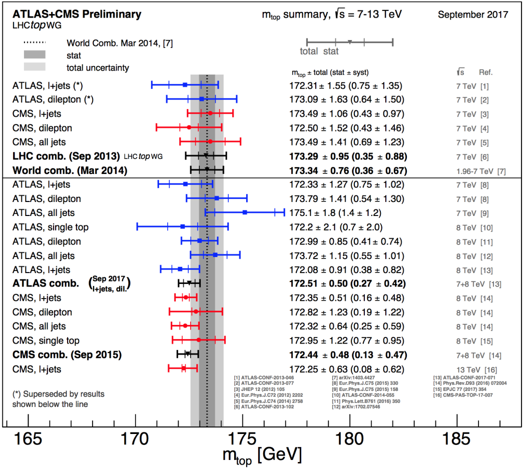
The quartic coupling λ_H becomes tiny at very high field values, and may turn negative, leading to vacuum instability.
M_t as low as 171 GeV leads to $\lambda_H \to 0$ at the Plank scale.

Do we need m_t with a precision better than 1 GeV?

- Precision physics: would need M_W with a precision below 15 MeV to match a precision of 1 GeV in the top mass.
- Vacuum stability: the only thing that we can infer is that we get no indication of a scale of new physics by requiring vacuum stability.

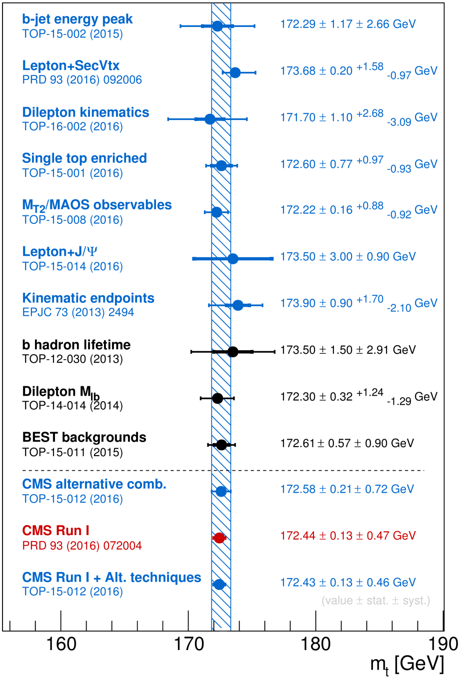
  Some authors emphasize the issue of ruling out absolute stability. However, this relies upon the extremely strong assumption that there is no new physics up to the Plank scale.
- Highly precise measurements would be easily achievable in e^+e^- colliders near the $t\bar{t}$ threshold
- The question of the ultimate precision that can be achieved in a top mass measurement at hadron colliders is a very interesting one, that challenges our understandin of hadron collider physics.

Top Mass Measurements



From kinematic reconstruction. Also called “standard” or “direct” methods.

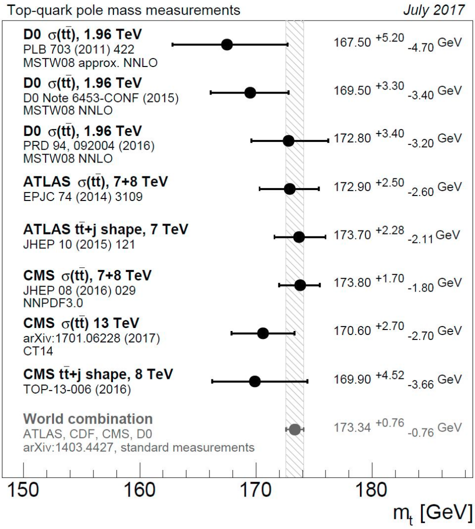
The most precise methods as of now.



Several methods explored by CMS (see PAS TOP-15-012).

Notice: they do not increase precision with respect to PRD 93 (2016) 072004, but show amazing consistency.

From total cross section and $t\bar{t}j$ kinematics



Sometimes quoted as "pole mass measurement"

WHY?

The “MC mass” theorem

- At LO in perturbation theory, one cannot distinguish between mass schemes (e.g. the pole mass is equal to the $\overline{\mathrm{MS}}$ mass).
- “Direct” mass measurements are performed using MC generators.
- MC generators are LO only.
- Hence: the extracted mass cannot be related to a well defined mass scheme. It is something that we can call “MC mass”.

Origin of the concept of “MC mass”

I do not know who started it, and I don’t remember the date of a conference in Italy where I first heard about it.

A written record can be found in

Alioli,Fernandez,Fuster,Irles,Moch,Uwer,2013:
“the top-quark mass derived from the kinematical reconstruction does not correspond to a well defined renormalization scheme leading to a theoretical uncertainty in its interpretation. Nevertheless it is usually interpreted as the top-quark pole mass”
not quoting any previous reference.

A reminder:

$$m_p^{\rm top} = m_{\overline{\rm MS}}^{\rm top} + \underbrace{7.557}_{\rm NLO} + \underbrace{1.617}_{\rm NNLO} + \underbrace{0.501}_{\rm N^3LO} + \underbrace{0.195 \pm 0.005}_{\rm N^4LO}\,{\rm GeV}$$

(fourth order term from Marquard,2×Smirnov,Steinhauser,2015).
Ambiguity on the mass scheme → ≈ 10 GeV uncertainty on $m_{\rm top}$.

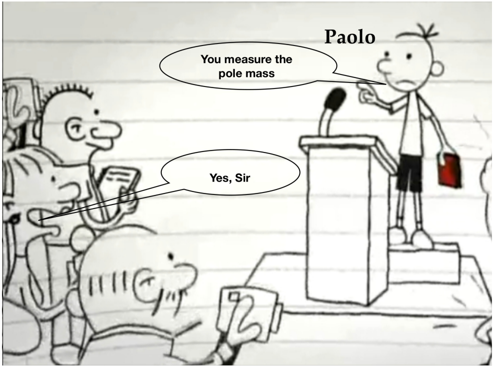
Dangers of “catchy” arguments

The argument gained quickly widespread acceptance among theorists (and seminated panic in the experimental community).

Often seen in experimental talks and papers that “direct” measurements measure the “Monte Carlo” mass (either this, or they do not say what they are measuring). So: a Standard Model parameter is measured with a precision of 4 parts in a thousand, but we don’t know what it is.

Direct measurements are separated from measurements performed in context where a choice of scheme is mandatory, like the mass extraction from the total cross section, or from the kinematic distributions in $t\bar{t}j$ events Alioli etal,2013.

In a recent talk on the top mass at the topLHCwg:
The top is the only SM particle with more than one mass
(it was a joke, of course ...)



(In the theory summary by Kirill Melnikov at the TOP2017 conference)

What's wrong with the argument

- In perturbation theory, and in the narrow width approximation, the top decay process factors away from the production process.
- In these approximation, if the pole mass scheme is used, the mass of the decay products equals the pole mass to all orders in α_s.
- It makes sense to consider observables that capture a consistent fraction of the decay products, like a W and a *b*-jet.
- Inaccuracies of the Monte Carlo (for being only LO, if this is the case) affect the fraction of particles that are *MISIDENTIFIED* as belonging or not belonging to the decay system by our observable.

What's wrong with the argument

We can add:

- Factorization of production and decay is a standard feature of shower Monte Carlo.
- Experimental collaborations now use (typically) the `POWHEG hvq`, or `MC@NLO` generators to model $t\bar{t}$ production, interfaced to Shower Monte Carlo's that implement Matrix-Element Corrections to top decay, essentially equivalent to NLO accuracy in decay for our purpose. Thus, even the correction to the misidentified decay products is simulated at the NLO level.

Complications

From Hoang,Stewart,2008:

"it is not m_t^{pole} that is being measured by the Tevatron analyses"

It is clear that Hoang,Stewart,2008 are arguing about non-perturbative differences and effects of order $\alpha_s \Gamma_t$. They argue that these differences are of order 1 GeV
(that at that time was the systematic error on the Tevatron measurement ...)

However, in Kieseler,Lipka,Moch,2016 we find:

At present, the translation from m_t^{MC} to a theoretically well-defined mass definition in a short-distance scheme at a low scale can only be estimated to be O(1) GeV, see, e.g., Ref. [8, 9].

In consequence, a measurement of m_t is preferable and can be performed by confronting a measured ob- servable sensitive to m_t with its prediction, calculated at NLO in QCD or beyond in a well-defined renormaliza- tion scheme for the top-quark mass.

where [8] is Hoang,Stewart,2008.

Complications

- Several publication followed where Hoang proposed to measure the top mass using boosted top jets, arguing that by using SCET power suppressed effects of Λ_{QCD}, that are not controlled in direct measurements, can be accounted for.
- The Pole Mass renormalon issue has been thrown into the mix, so that it was argued that a low-scale $\overline{\mathrm{MSr}}$ mass should be used instead.
- Attempt to relate this $\overline{\mathrm{MSr}}$ mass to the Pythia8 mass were performed yielding an MC mass that exceeds the $\overline{\mathrm{MSr}}$ mass by about 200 MeV. But since also the pole mass exceeds the $\overline{\mathrm{MSr}}$ mass by few hundred MeV (I get roughly 300), it seems difficult to keep arguing that on this basis the MC mass should be different from the pole mass.
- The pole mass renormalon problem has been shown to be not very relevant for the top, yielding to an uncertainty of 110 MeV (Hoang says now 250 MeV).

Conclusions

- "MC mass": beware of catchy concepts
- Collider mass measurements are affected by hard to quantify non-perturbative effects. Until we have a solid theory of linear power suppressed effects at colliders, we should acknowledge this.
- A lot can be done with shower Monte Carlo to make educated upper bounds on these power effects (this is partly already done by the experimental collaborations). After all, Monte Carlo fit the data, so they must be doing something right.
- The top statistics is enormous, and it will become even bigger at the HL-HLC. Lot of room to measure the mass in restricted regions of phase space, or using complementary methods.
- Consistency among different determinations will give us confidence on our methods to determine the error.
- Think more: not so much to find new ways to measure the top mass, but to find how to estimate the error in the current most precise ones.